

(12) **United States Patent**
Cernea

(10) **Patent No.:** **US 9,123,430 B2**
(45) **Date of Patent:** **Sep. 1, 2015**

(54) **DIFFERENTIAL CURRENT SENSE
AMPLIFIER AND METHOD FOR
NON-VOLATILE MEMORY**

(71) Applicant: **SanDisk 3D LLC**, Milpitas, CA (US)

(72) Inventor: **Raul Adrian Cernea**, Santa Clara, CA
(US)

(73) Assignee: **SANDISK 3D LLC**, Milpitas, CA (US)

(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 221 days.

(21) Appl. No.: **13/918,833**

(22) Filed: **Jun. 14, 2013**

(65) **Prior Publication Data**

US 2014/0369132 A1 Dec. 18, 2014

(51) **Int. Cl.**
G11C 16/06 (2006.01)
G11C 16/28 (2006.01)
G11C 7/06 (2006.01)

(52) **U.S. Cl.**
CPC **G11C 16/28** (2013.01); **G11C 7/062**
(2013.01); **G11C 2207/063** (2013.01)

(58) **Field of Classification Search**
CPC ... G11C 16/28; G11C 7/062; G11C 2207/063
USPC 365/185.09, 185.21, 185.22
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,570,315 A 10/1996 Tanaka et al.
5,774,397 A 6/1998 Endoh et al.
6,046,935 A 4/2000 Takeuchi et al.
6,373,746 B1 4/2002 Takeuchi et al.

6,456,528 B1 9/2002 Chen
6,522,580 B2 2/2003 Chen et al.
6,643,188 B2 11/2003 Tanaka et al.
6,771,536 B2 8/2004 Li et al.
6,781,877 B2 8/2004 Cernea et al.
7,016,226 B2 * 3/2006 Shibata et al. 365/185.03
7,016,230 B2 * 3/2006 Hosono 365/185.17
7,023,739 B2 4/2006 Chen et al.
7,064,568 B2 6/2006 Hunt et al.
7,177,191 B2 2/2007 Fasoli et al.
7,342,279 B2 3/2008 Harari et al.
7,443,757 B2 * 10/2008 Cernea et al. 365/226
2002/0051384 A1 5/2002 Cernea et al.
2006/0158935 A1 7/2006 Chan et al.
2006/0184720 A1 8/2006 Sinclair et al.
2009/0080265 A1 3/2009 Mokhlesi et al.

OTHER PUBLICATIONS

Notification of Transmittal of the International Search Report and
the Written Opinion of the International Searching Authority, or the
Declaration for Int'l Application No. PCT/US2014/040925 mailed
on Nov. 7, 2014, 9 pages.

* cited by examiner

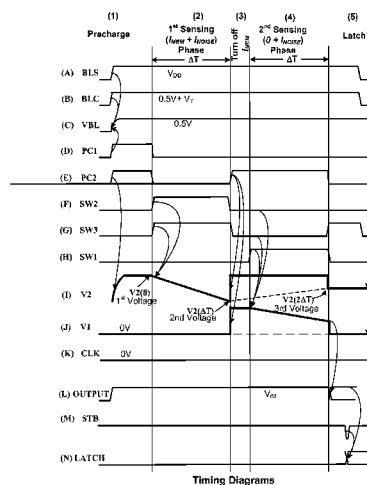
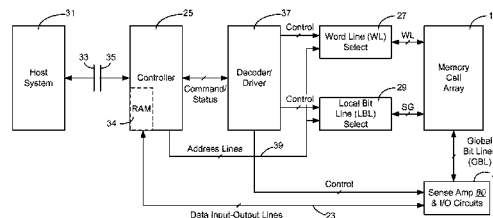
Primary Examiner — Thao H Bui

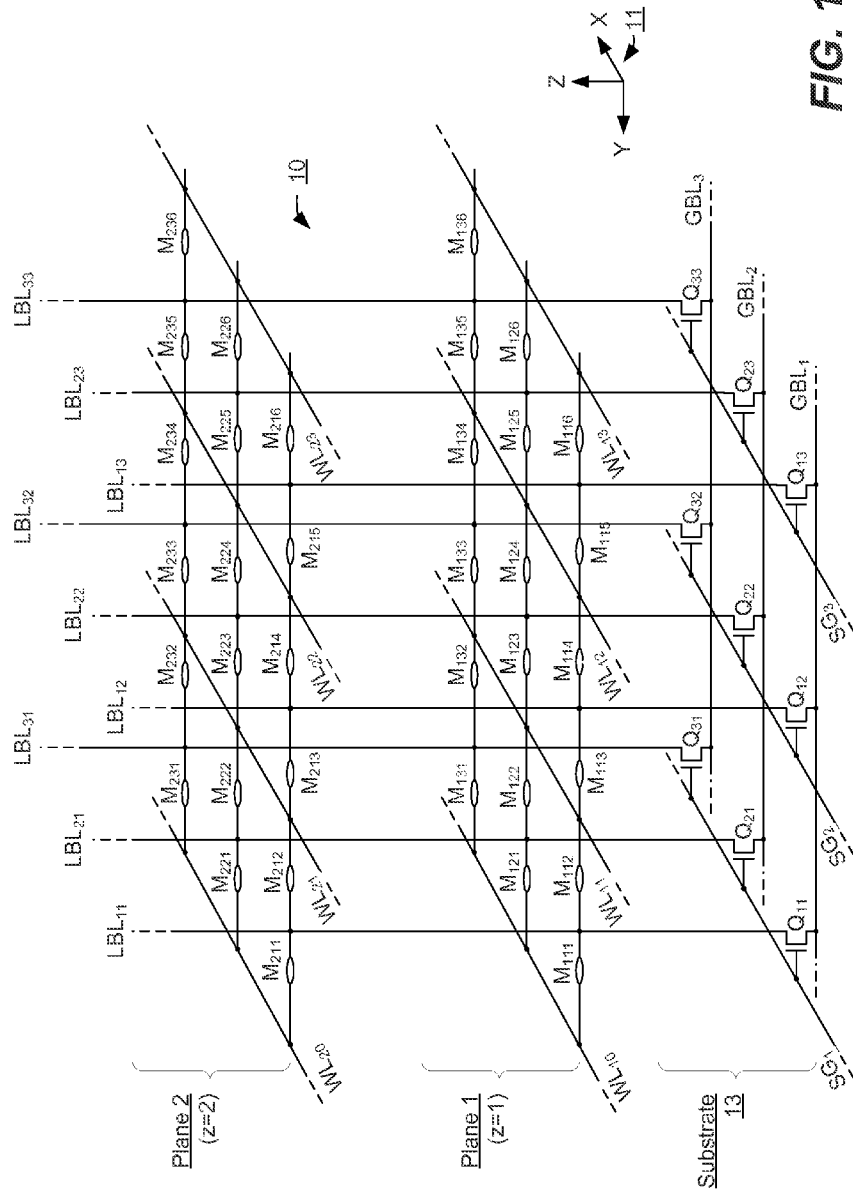
(74) *Attorney, Agent, or Firm* — Davis Wright Tremaine
LLP

(57) **ABSTRACT**

The selected bit line in a non-volatile memory carries a cell
conduction current to be measured and also a leakage current
or noise due to weak coupling with neighboring array struc-
tures. In a first phase, a sense amplifier senses the bit line
current by discharging a capacitor with the combined current
(cell conduction current plus the leakage current) over a pre-
determined time. In a second phase, the cell conduction cur-
rent is minimized and significantly the leakage current in the
selected bit line is used to recharge in tandem the capacitor in
a time same as the predetermined time, effectively subtracting
the component of the leakage current measured in the first
sensing phase. The resultant voltage drop on the capacitor
over the two sensing phases provides a measure of the cell
conduction current alone, thereby avoiding reading errors due
to the leakage current present in the selected bit line.

18 Claims, 6 Drawing Sheets





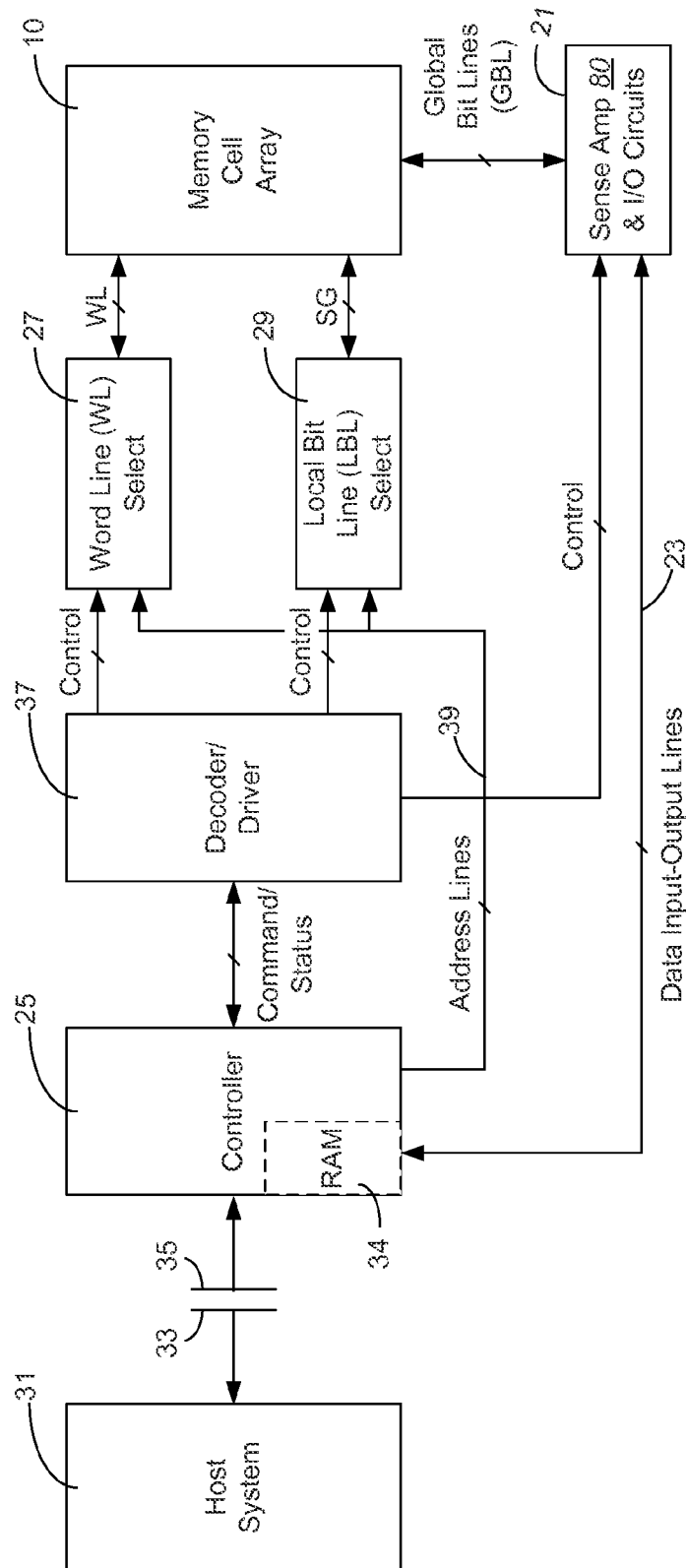
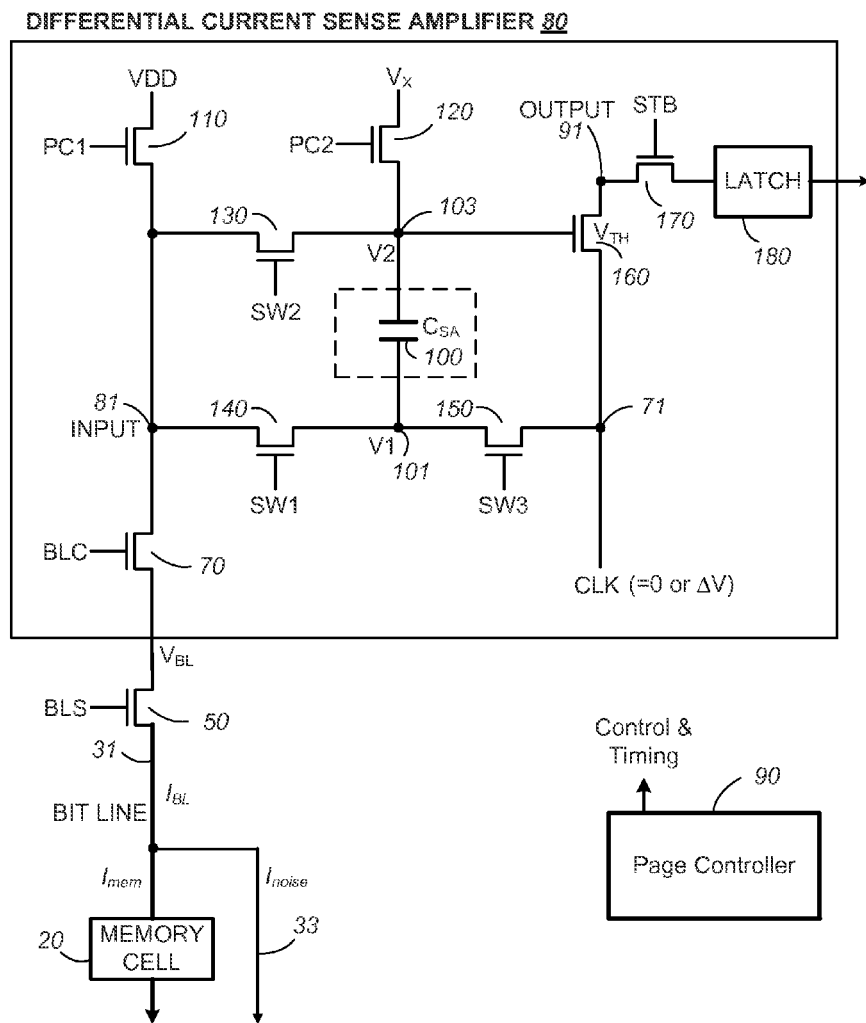
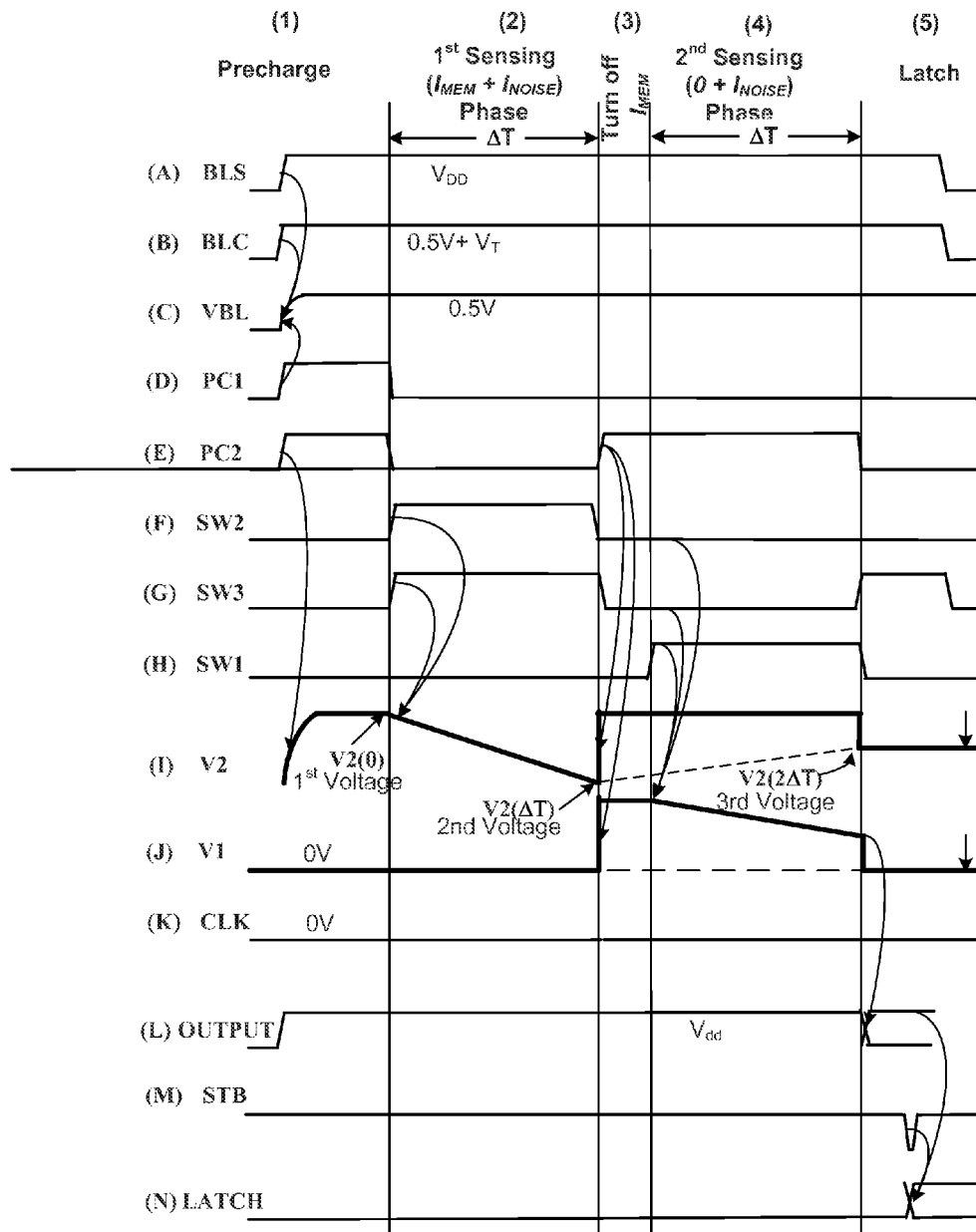


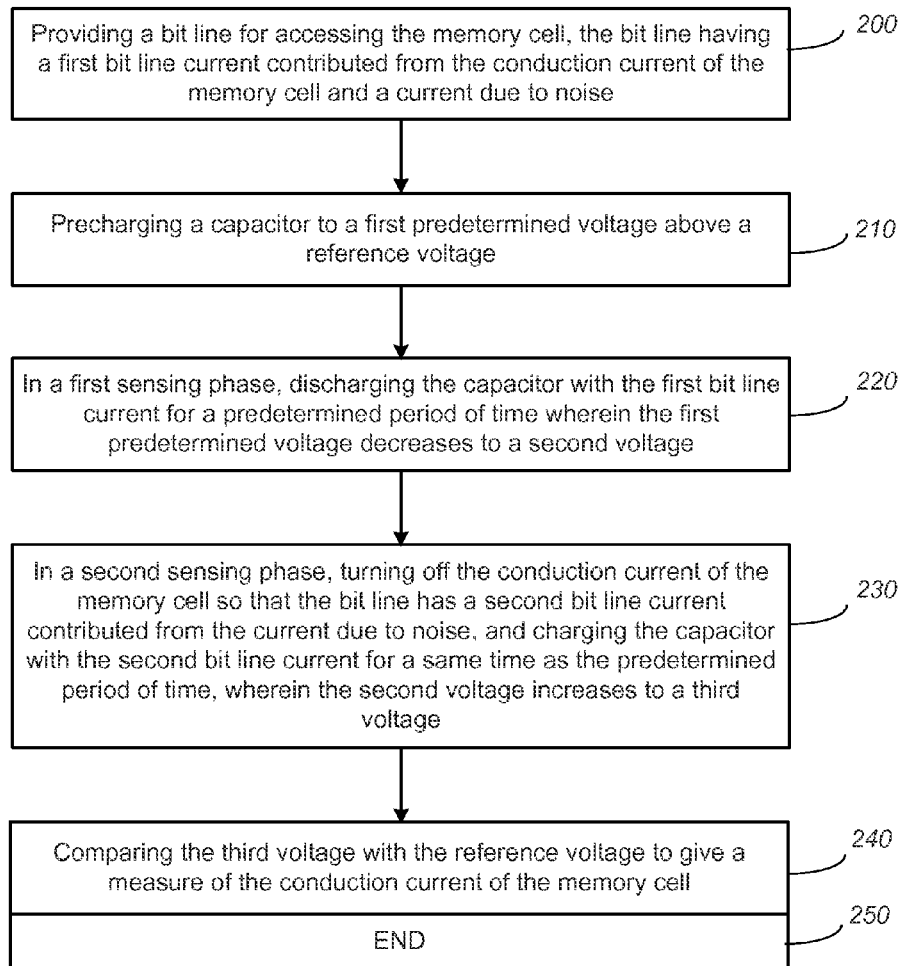
FIG. 2

**FIG. 3**



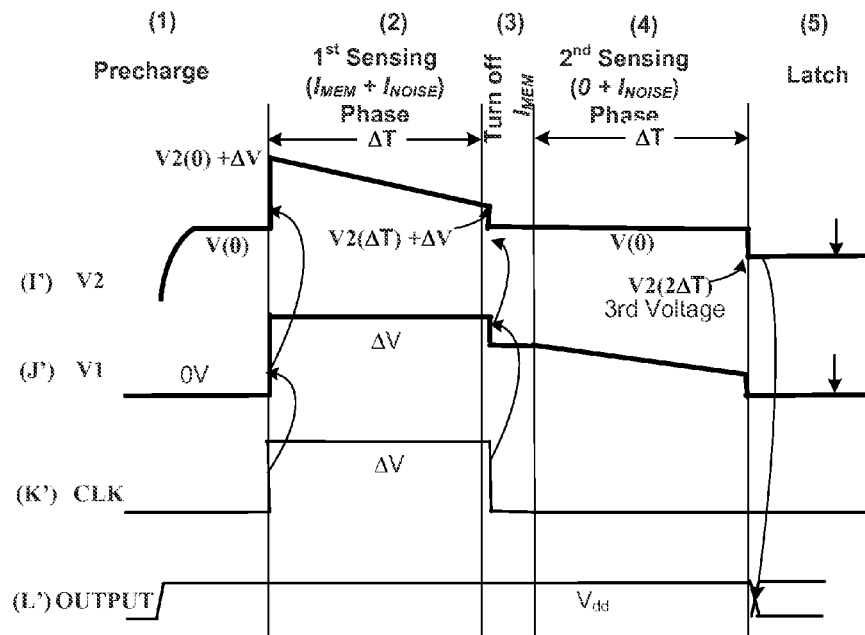
Timing Diagrams

FIG. 4



Differential Current Sensing

FIG. 5



Timing Diagrams for Current Sensing with Low-Voltage Operation

FIG. 6

In a first sensing phase, discharging the capacitor with the first bit line current for a predetermined period of time wherein the first predetermined voltage decreases to a second voltage; and wherein the capacitor is provided with first and second terminals, the second terminal being operated at a higher voltage level than the first terminal and with a predetermined boosting voltage applied temporarily to the first terminal during the first sensing phase

220'

Differential Current Sensing with Low-Voltage Operation

FIG. 7

DIFFERENTIAL CURRENT SENSE AMPLIFIER AND METHOD FOR NON-VOLATILE MEMORY

BACKGROUND

The subject matter of this application is sensing circuits and methods for sensing conduction currents that correspond to memory states of non-volatile memory cells.

Uses of re-programmable non-volatile mass data storage systems utilizing flash memory are widespread for storing data of computer files, camera pictures, and data generated by and/or used by other types of hosts. A popular form of flash memory is a card that is removably connected to the host through a connector. There are many different flash memory cards that are commercially available, examples being those sold under trademarks CompactFlash (CF), the MultiMediaCard (MMC), Secure Digital (SD), miniSD, microSD, Memory Stick, Memory Stick Micro, xD-Picture Card, SmartMedia and TransFlash. These cards have unique mechanical plugs and/or electrical interfaces according to their specifications, and plug into mating receptacles provided as part of or connected with the host.

Another form of flash memory systems in widespread use is the flash drive, which is a hand held memory system in a small elongated package that has a Universal Serial Bus (USB) plug for connecting with a host by plugging it into the host's USB receptacle. SanDisk Corporation, assignee hereof, sells flash drives under its Cruzer, Ultra and Extreme Contour trademarks. In yet another form of flash memory systems, a large amount of memory is permanently installed within host systems, such as within a notebook computer in place of the usual disk drive mass data storage system. Each of these three forms of mass data storage systems generally includes the same type of flash memory arrays. They each also usually contain its own memory controller and drivers but there are also some memory only systems that are instead controlled at least in part by software executed by the host to which the memory is connected. The flash memory is typically formed on one or more integrated circuit chips and the controller on another circuit chip. But in some memory systems that include the controller, especially those embedded within a host, the memory, controller and drivers are often formed on a single integrated circuit chip.

There are two primary techniques by which data are communicated between the host and flash memory systems. In one of them, addresses of data files generated or received by the system are mapped into distinct ranges of a continuous logical address space established for the system. The extent of the address space is typically sufficient to cover the full range of addresses that the system is capable of handling. As one example, magnetic disk storage drives communicate with computers or other host systems through such a logical address space. The host system keeps track of the logical addresses assigned to its files by a file allocation table (FAT) and the memory system maintains a map of those logical addresses into physical memory addresses where the data are stored. Most memory cards and flash drives that are commercially available utilize this type of interface since it emulates that of magnetic disk drives with which hosts have commonly interfaced.

In the second of the two techniques, data files generated by an electronic system are uniquely identified and their data logically addressed by offsets within the file. These file identifiers are then directly mapped within the memory system into physical memory locations. Both types of host/

memory system interfaces are described and contrasted elsewhere, such as in patent application publication no. US 2006/0184720 A1.

Flash memory systems typically utilize integrated circuits with arrays of memory cells that individually store an electrical charge that controls the threshold level of the memory cells according to the data being stored in them. Electrically conductive floating gates are most commonly provided as part of the memory cells to store the charge but dielectric charge trapping material is alternatively used. A NAND architecture is generally preferred for the memory cell arrays used for large capacity mass storage systems. Other architectures, such as NOR, are typically used instead for small capacity memories. Examples of NAND flash arrays and their operation as part of flash memory systems may be had by reference to U.S. Pat. Nos. 5,570,315, 5,774,397, 6,046,935, 6,373,746, 6,456,528, 6,522,580, 6,643,188, 6,771,536, 6,781,877 and 7,342,279.

The amount of integrated circuit area necessary for each bit of data stored in the memory cell array has been reduced significantly over the years, and the goal remains to reduce this further. The cost and size of the flash memory systems are therefore being reduced as a result. The use of the NAND array architecture contributes to this but other approaches have also been employed to reducing the size of memory cell arrays. One of these other approaches is to form, on a semiconductor substrate, multiple two-dimensional memory cell arrays, one on top of another in different planes, instead of the more typical single array. Examples of integrated circuits having multiple stacked NAND flash memory cell array planes are given in U.S. Pat. Nos. 7,023,739 and 7,177,191.

Another type of re-programmable non-volatile memory cell uses variable resistance memory elements that may be set to either conductive or non-conductive states (or, alternately, low or high resistance states, respectively), and some additionally to partially conductive states and remain in that state until subsequently re-set to the initial condition. The variable resistance elements are individually connected between two orthogonally extending conductors (typically bit lines and word lines) where they cross each other in a two-dimensional array. The state of such an element is typically changed by proper voltages being placed on the intersecting conductors. Since these voltages are necessarily also applied to a large number of other unselected resistive elements because they are connected along the same conductors as the states of selected elements being programmed or read, leakage currents can flow through them. When the memory state of a memory cell is read by measuring its conduction current, the reading may be erroneous due to the existence of noise such as an additional leakage current.

The desire to perform data reading and programming operations with a large number of memory cells in parallel results in reading voltages being applied to a very large number of other memory cells and the issue of managing leakage currents to minimize the problems of errors and loss of margin during read operations.

SUMMARY OF THE INVENTION

Differential Current Sensing

A memory cell in a memory array is accessible by a pair of selected word line and bit line. When appropriate bias voltages are applied to the pair of selected word line and bit line, the memory cell will have a cell conduction current depending on its memory state.

The selected bit line carrying the cell conduction current may also have a leakage current or noise component due to

3

weak coupling with neighboring array structures. A sense amplifier sensing from the selected bit line over two sensing phases is able to differentiate the cell conduction current from the leakage current. In a first phase, the sense amplifier senses the bit line current by discharging a capacitor with the combined current (cell conduction current plus the leakage current) over a predetermined time. In a second phase, the cell conduction current is minimized and significantly the leakage current in the selected bit line is used to recharge in tandem the capacitor in a time same as the predetermined time, effectively subtracting the leakage current component included in the first sensing phase. The resultant voltage drop on the capacitor over the two sensing phases provides a measure of the cell conduction current alone, thereby avoiding reading errors due to the leakage current present in the selected bit line.

According to one aspect of the invention, a method of sensing a conduction current of a memory cell includes providing a bit line for accessing the memory cell, the bit line having a first bit line current constituted from the conduction current of the memory cell and a current due to noise; precharging a capacitor to a first predetermined voltage above a reference voltage; and in a first sensing phase, discharging the capacitor with the first bit line current for a predetermined period of time wherein the first predetermined voltage decreases to a second voltage; and in a second sensing phase, minimizing the conduction current of the memory cell so that the bit line has a second bit line current significantly constituted from the current due to noise, and charging the capacitor with the second bit line current for a same time as the predetermined period of time, wherein the second voltage increases to a third voltage; and comparing the third voltage with the reference voltage to give a measure of the conduction current of the memory cell.

According to another embodiment of the invention, the method further includes temporarily boosting the voltages at the capacitor by a predetermined boosting voltage during the first sensing phase to provide more headroom.

According to another aspect of the invention, a sense amplifier for sensing a conduction current of a memory cell of a non-volatile memory includes a bit line for accessing the memory cell, the bit line having a first bit line current constituted from the conduction current of the memory cell and a current due to noise; a bit line voltage circuit for maintain the bit line at a predetermined voltage; a capacitor; a precharging circuit coupled to said capacitor to precharge the capacitor to a first predetermined voltage above a reference voltage; and in a first sensing phase, a first set of signals to enable said capacitor to be coupled for discharging by the first bit line current for a predetermined period of time wherein the first predetermined voltage decreases to a second voltage; and in a second sensing phase, where the memory cell has the conduction current minimized so that the bit line has a second bit line current significantly constituted from the current due to noise, and a second set of signals to enable said capacitor to be coupled for charging by the second bit line current for a same time as the predetermined period of time, wherein the second voltage increases to a third voltage; and a comparator for comparing the third voltage with the reference voltage to give a measure of the conduction current of the memory cell.

Various aspects, advantages, features and details of the innovative three-dimensional variable resistive element memory system are included in a description of exemplary examples thereof that follows, which description should be taken in conjunction with the accompanying drawings.

All patents, patent applications, articles, other publications, documents and things referenced herein are hereby

4

incorporated herein by this reference in their entirety for all purposes. To the extent of any inconsistency or conflict in the definition or use of terms between any of the incorporated publications, documents or things and the present application, those of the present application shall prevail.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates schematically an architecture of a three-dimensional memory in the form of an equivalent circuit of a portion of such a memory.

FIG. 2 is a block diagram of an illustrative memory system that can use the three-dimensional memory of FIG. 1.

FIG. 3 illustrates a sense amplifier for sensing differential current of a memory cell.

FIGS. 4(A)-4(N) are timing diagrams illustrating schematically the operations of the sense amplifier shown in FIG. 3.

FIG. 5 is a flow diagram illustrating a method of sensing the conduction current of the memory cell.

FIG. 6 is a timing diagram illustrating a preferred embodiment for low-voltage operating the sense amplifier 80 shown in FIG. 3.

FIG. 7 is a flow diagram illustrating another embodiment of the method of sensing the conduction current of the memory cell under low-voltage condition.

DESCRIPTION OF EXEMPLARY EMBODIMENTS

FIG. 1 illustrates schematically an example of a memory 10 having a three-dimensional array of memory elements or cells. An equivalent circuit of a portion of such a memory is shown. A standard three-dimensional rectangular coordinate system 11 is used for reference, the directions of each of vectors x, y and z being orthogonal with the other two.

A circuit for selectively connecting internal memory elements with external data circuits is preferably formed in a semiconductor substrate 13. In this specific example, a two-dimensional array of select or switching devices Q_{xy} are utilized, where x gives a relative position of the device in the x-direction and y its relative position in the y-direction. The individual devices Q_{xy} may be a select gate or select transistor, as examples. Global bit lines (GBL_x) are elongated in the y-direction and have relative positions in the x-direction that are indicated by the subscript. The global bit lines (GBL_x) are individually connectable with the source or drain of the select devices Q having the same position in the x-direction, although during reading and also typically programming only one select device connected with a specific global bit line is turned on at time. The other of the source or drain of the individual select devices Q is connected with one of the local bit lines (LBL_{xy}). The local bit lines are elongated vertically, in the z-direction, and form a regular two-dimensional array in the x (row) and y (column) directions.

In order to connect one set (in this example, designated as one row) of local bit lines with corresponding global bit lines, control gate lines SG_x are elongated in the x-direction and connect with control terminals (gates) of a single row of select devices Q_{xy} having a common position in the y-direction. The select devices Q_{xy} therefore connect one row of local bit lines (LBL_{xy}) across the x-direction (having the same position in the y-direction) at a time to corresponding ones of the global bit-lines (GBL_x), depending upon which of the control gate lines SG_x receives a voltage that turns on the select devices to which it is connected. The remaining control gate lines receive voltages that keep their connected select devices off.

5

It may be noted that since only one select device (Q_{xy}) is used with each of the local bit lines (LBL_{xy}), the pitch of the array across the semiconductor substrate in both x and y-directions may be made very small, and thus the density of the memory storage elements large.

Memory storage elements M_{zxy} are formed in a plurality of planes positioned at different distances in the z-direction above the substrate 13. Two planes 1 and 2 are illustrated in FIG. 1 but there will typically be more, such as 4, 6 or even more. In each plane at distance z, word lines WL_{zy} are elongated in the x-direction and spaced apart in the y-direction between the local bit-lines (LBL_{xy}). The word lines WL_{zy} of each plane individually cross adjacent two of the local bit-lines LBL_{xy} on either side of the word lines. The individual memory storage elements M_{zxy} are connected between one local bit line LBL_{xy} and one word line WL_{zy} adjacent these individual crossings. An individual memory element M_{zxy} is therefore addressable by placing proper voltages on the local bit line LBL_{xy} and word line WL_{zy} between which the memory element is connected. The voltages are chosen to provide the electrical stimulus necessary to cause the state of the memory element to change from an existing state to the desired new state. The levels, duration and other characteristics of these voltages depend upon the material that is used for the memory elements.

Each "plane" of the three-dimensional memory cell structure is typically formed of at least two layers, one in which the conductive word lines WL_{zy} are positioned and another of a dielectric material that electrically isolates the planes from each other. Additional layers may also be present in each plane, depending for example on the structure of the memory elements M_{zxy} . The planes are stacked on top of each other on a semiconductor substrate with the local bit lines LBL_{xy} being connected with storage elements M_{zxy} of each plane through which the local bit lines extend.

FIG. 2 is a block diagram of an illustrative memory system that can use the three-dimensional memory 10 of FIG. 1. Sense amplifier and I/O circuits 21 are connected to provide (during programming) and receive (during reading) analog electrical quantities in parallel over the global bit-lines GBL_x of FIG. 1 that are representative of data stored in addressed storage elements M_{zxy} . The circuits 21 typically contain sense amplifiers for converting these electrical quantities into digital data values during reading, which digital values are then conveyed over lines 23 to a memory system controller 25. Conversely, data to be programmed into the array 10 are sent by the controller 25 to the sense amplifier and I/O circuits 21, which then programs that data into addressed memory element by placing proper voltages on the global bit lines GBL_x . For binary operation, one voltage level is typically placed on a global bit line to represent a binary "1" and another voltage level to represent a binary "0". The memory elements are addressed for reading or programming by voltages placed on the word lines WL_{zy} and select gate control lines SG_y by respective word line select circuits 27 and local bit line circuits 29. In the specific three-dimensional array of FIG. 1, the memory elements lying between a selected word line and any of the local bit lines LBL_{xy} connected at one instance through the select devices Q_{xy} to the global bit lines GBL_x may be addressed for programming or reading by appropriate voltages being applied through the select circuits 27 and 29.

The memory system controller 25 typically receives data from and sends data to a host system 31. The controller 25 usually contains an amount of random-access-memory (RAM) 34 for temporarily storing such data and operating information. Commands, status signals and addresses of data being read or programmed are also exchanged between the

6

controller 25 and host 31. The memory system operates with a wide variety of host systems. They include personal computers (PCs), laptop and other portable computers, cellular telephones, personal digital assistants (PDAs), digital still cameras, digital movie cameras and portable audio players. The host typically includes a built-in receptacle 33 for one or more types of memory cards or flash drives that accepts a mating memory system plug 35 of the memory system but some hosts require the use of adapters into which a memory card is plugged, and others require the use of cables therebetween. Alternatively, the memory system may be built into the host system as an integral part thereof.

The memory system controller 25 conveys to decoder/driver circuits 37 commands received from the host. Similarly, status signals generated by the memory system are communicated to the controller 25 from the circuits 37. The circuits 37 can be simple logic circuits in the case where the controller controls nearly all of the memory operations, or can include a state machine to control at least some of the repetitive memory operations necessary to carry out given commands. Control signals resulting from decoding commands are applied from the circuits 37 to the word line select circuits 27, local bit line select circuits 29 and sense amplifier and I/O circuits 21. Also connected to the circuits 27 and 29 are address lines 39 from the controller that carry physical addresses of memory elements to be accessed within the array 10 in order to carry out a command from the host. The physical addresses correspond to logical addresses received from the host system 31, the conversion being made by the controller 25 and/or the decoder/driver 37. As a result, the circuits 29 partially address the designated storage elements within the array 10 by placing proper voltages on the control elements of the select devices Q_{xy} to connect selected local bit lines (LBL_{xy}) with the global bit lines (GBL_x). The addressing is completed by the circuits 27 applying proper voltages to the word lines WL_{zy} of the array.

Although the memory system of FIG. 2 utilizes the three-dimensional memory element array 10 of FIG. 1, the system is not limited to use of only that array architecture. A given memory system may alternatively combine this type of memory with other another type including flash memory, such as flash having a NAND memory cell array architecture, a magnetic disk drive or some other type of memory. The other type of memory may have its own controller or may in some cases share the controller 25 with the three-dimensional memory cell array 10, particularly if there is some compatibility between the two types of memory at an operational level.

A memory cell in the memory array 10 is accessible by a pair of selected word line and bit line. When appropriate bias voltages are applied to the pair of selected word line and bit line, the memory cell will have a cell conduction current depending on its memory state.

Although each of the memory elements M_{zxy} in the array of FIG. 1 may be individually addressed for changing its state according to incoming data or for reading its existing storage state, it is certainly preferable to program and read the array in units of multiple memory elements in parallel. In the three-dimensional array of FIG. 1, one row of memory elements on one plane may be programmed and read in parallel. The number of memory elements operated in parallel depends on the number of memory elements connected to the selected word line. For example, in a read operation, all word lines and bit lines in the array are set to 0.5V except the selected word line (e.g., WL_{10}) which is set to 0V. This will set up a voltage difference of 0.5 across a page of memory cells (e.g., M_{211} ,

M_{221}, M_{231}, \dots) suitable for reading their conduction currents via their respective local and global bit lines.

However, in practice parasitic currents occur due to coupling of neighboring structures. Thus the bit lines also carry these parasitic currents as leakage currents, which are noise to the cell current being measured. Parasitic currents during such a read operation have two undesirable effects. As with programming, parasitic currents place increased demands on the memory system power supply. In addition, it is possible for parasitic currents to exist that are erroneously included in the currents though the addressed memory elements that are being read. This can therefore lead to erroneous read results if such parasitic currents are large enough.

U.S. Pat. No. 7,064,568 describes a sense amplifier suitable for sensing conduction current of a memory cell in a NAND memory without the ability to differentiate from any leakage current in a selected bit line.

U.S. application Ser. No. 13/794,344, filed on Mar. 11, 2013, "Non-Volatile Memory Having 3D Array Architecture with Bit Line Voltage Control and Methods Thereof" discusses the problem of leakage currents during read operations.

The level of parasitic currents increases with the number of planes and with the number of memory elements connected along the individual word lines within each plane. But since the number of word lines on each plane does not significantly affect the amount of parasitic current, the planes may individually include a large number of word lines.

Sense Amplifier for Sensing Differential Currents in a Memory

In many memory arrays, the memory cells in the array are accessed by a lattice of array elements such as interconnected word lines, bit lines and memory cells. The biasing conditions on the selected word line and bit lines and the unselected word lines and bit lines are such that a leakage current I_{NOISE} may appear in the selected bit line **31** in which I_{MEM} is to be detected.

FIG. 3 illustrates a sense amplifier for sensing differential current in the selected bit line **31**. A sense amplifier **80** is able to sense and differentiate the conduction current I_{MEM} in the selected bit line **31** from any leakage current I_{NOISE} contributed from a current branch **33**. When a memory cell **20** is turned on, its memory state can be read by sensing the magnitude of its conduction current I_{MEM} . Typically, the memory cell being sensed is among a page of such memory cells in a memory array being sensed in parallel. Each memory cell **20** of the page is accessed by a corresponding bit line **31**, which is selected by decoding the bit line select signal BLS to connect the selected bit line **31** via a bit line select switch **50** to a corresponding sense amplifier **80**.

The sense amplifier **80** essentially measures the bit line current by the rate it discharges a capacitor C_{SA} **100**. The faster the discharge, the larger is the current. In a first phase, the sense amplifier **80** senses the bit line current by discharging the capacitor C_{SA} **100** with the combined current ($I_{MEM} + I_{NOISE}$) over a predetermined time. In a second phase, the cell conduction current is minimized so that the leakage current I_{NOISE} is the significant current in the selected bit line to recharge in tandem the capacitor in a time same as the predetermined time, effectively subtracting the component of the leakage current measured in the first sensing phase. This is accomplished by reversing the connection of the bit line to the terminals of the capacitor relative to the first sensing phase. The resultant voltage drop on the capacitor over the two sensing phases provides a measure of the cell conduction current alone, thereby avoiding reading errors due to the leakage current present in the selected bit line.

The capacitor C_{SA} **100** has a first terminal **101** and a second terminal **103**. The first terminal **101** has a voltage $V1$ and the second terminal **103** has a voltage $V2$ higher than $V1$.

The sense amplifier **80** has the bit line current throw through an INPUT node **81** from the bit line **31** via a bit line voltage clamp **70**. The INPUT node **81** is able to couple to the second terminal **103** via a transistor switch **130** that is controlled by a signal SW2. The INPUT node **81** is also able to couple to the first terminal **101** via a transistor switch **140** that is controlled by a signal SW1.

Also the INPUT node **81** is able to be precharged by a precharge driver **110**. The precharge driver **110** has its drain at VDD and its source connected to the INPUT node **81** and its gate controlled by a signal PC1.

The bit line voltage is maintained by the sense amplifier **80** with the precharge driver **110** and the bit line voltage clamp transistor **70** in series with the bit line **31**. To maintain the bit line at V_{BL} , the transistor **70** operates like a diode clamp with its source coupled to the bit line **31** and its drain connected to the INPUT node **101** of the sense amplifier **80**. It has a gate voltage set to $V_{BL} + V_T$, where V_T is the threshold voltage. In this way, the bit line voltage clamp **70** isolates the bit line **31** from the INPUT node **81** and sets a constant voltage level for the bit line such as for example $V_{BL} = 0.5$ to 0.7 volts. For the bit line voltage clamp transistor **70** to function, its drain voltage at the INPUT node **101** has to be greater than its source voltage, i.e., greater than V_{BL} .

The first terminal **101** of the capacitor C_{SA} **100** is at a voltage $V1$ and can be coupled to a clock signal CLK at a node **71** when a connecting transistor switch **150** as controlled by a signal SW3, is turned on. In one embodiment, the clock signal CLK is always at $0V$. In another embodiment as will be described later, the clock signal CLK has two states, which is either at $0V$ or during the first sensing phase boosted by a predetermined ΔV .

The first terminal **101**, as described earlier, can also be selectively coupled to the INPUT node **81** via the transistor switch **140** during the second sensing phase.

The second terminal **103** of the capacitor C_{SA} **100** is at a voltage $V2$. It can be precharged by a precharge driver **120** with its drain at V_X (which can be another supply voltage higher than VDD) and controlled by a signal PC2. It is selectively coupled to the INPUT node **81** via the transistor switch **130** during the first sensing phase.

The second terminal **103** is also connected to a gate of a discriminating transistor **160**. The discriminating transistor **160** has its source and drain across the node **71** and an OUTPUT node **91**. The voltage level at the OUTPUT node **91** can be saved in a latch **180** when a transistor switch **170** is turned on by a signal STB.

In general, there will be a page of memory cells being operated on in parallel by a corresponding number of sense amplifiers **80**. The page of memory cells is selected by a selected word line and a page of selected bit lines. A page controller **90** supplies control and timing signals to each of the sense amplifiers. In one embodiment, the page controller **90** is implemented as part of a state machine in a control circuitry on a memory chip.

FIGS. 4(A)-4(N) are timing diagrams illustrating schematically the operations of the sense amplifier **80** shown in FIG. 3.

Precharge Phase

The bit line **31** is selected by the signal BLS going to VDD to turn on the select transistor **50** (FIG. 4(A)(1)).

Both the bit line **31** and the second terminal **103** of the capacitor C_{SA} **100** are to be precharged. The bit line **31** is precharged to V_{BL} by the precharge driver **110** with PC1

HIGH. The second terminal **103** is initially precharged to a voltage $V_2(0)$ by the precharge driver **120** with PC2 HIGH. When precharge is completed, the signals PC1 and PC2 go LOW to turn off the precharge driver **110** and the precharge driver **120** respectively (FIGS. 4(B)(1)-4(E)(1)). First Sensing Phase for Sensing the Combined Current ($I_{BL}=I_{MEM}+I_{NOISE}$)

The current to discharge the capacitor C_{SA} **100** is provided by the current in the bit line **31**, which is $I_{BL}=I_{MEM}+I_{NOISE}$. The memory cell has the conduction current I_{MEM} when it is turned on with the bit line voltage biased to V_{BL} .

The sense amplifier **80** determines the magnitude of the bit line current I_{BL} by measuring the rate it discharges a capacitor C_{SA} **100**. The bit line **31** via the INPUT node **81** is coupled to the second terminal **103** when the signal SW2 goes HIGH. Also with SW3 HIGH, the first terminal **101** is coupled to the node **71** to CLK which is at 0V. This will enable the bit line current I_{BE} to discharge the capacitor C_{SA} **100**. The rate of discharge is effectively determined by noting the drop, after a predetermined discharge period ΔT , of the voltage V_2 from $V_2(0)$ to $V_2(\Delta T)$. See FIG. 4(F)(2)-4(K)(2).

Second Sensing Phase for Sensing and Subtracting the Noise Current ($I_{BL}=I_{NOISE}$)

In this phase, the INPUT node **81** is switch from the second terminal **103** to the first terminal **101**. This is accomplished by turning off the transistor switch **130** and turning on the transistor switch **140** disposed between the INPUT node **81** and the first terminal **101**. The second terminal **103** is then powered by turning on the precharge driver **120** with PC2 going HIGH. This will set $V_2=V_1=V_2(0)$. The transistor switch **140** is controlled by the signal SW1. This allows the first terminal **101** to be exclusively connected to the INPUT node **81** when the transistor switch **150** between the first terminal **101** and the node **71** to CLK is turned off by the signal SW3.

With this setup, the memory cell **20** is minimized with $I_{MEM}\sim 0$ and $I_{BE}\sim I_{NOISE}$. This is accomplished by biasing the selected word line (not shown in FIG. 3) to the same voltage as the selected bit line **31**. Now, with the INPUT node **81** connected to the capacitor C_{SA} **100** in reverse, the leakage current I_{NONE} is effectively used to charge the capacitor C_{SA} **100** instead. (It is really pulling V_1 down to increase the voltage difference across the capacitor.) The charging is allowed for a time same as the predetermined period ΔT in the first sensing phase so that it cancels the discharging effect of the I_{NOISE} component in the first sensing phase. At the end of the predetermined period, V_1 is reset to 0V by connecting back to CLK at node **71**. This will also shift V_2 down to effectively have the previous $V_2(\Delta T)$ at the second terminal **103** is increased to $V_2(2\Delta T)$. This final voltage corresponds to the discharging effect of only I_{MEM} on the capacitor C_{SA} **100** and is a measure of I_{MEM} without the interference of I_{NOISE} . See FIGS. 4(F)(3)-4(K)(3)(4).

The result $V_2(2\Delta T)$ can now be measured by the discriminating transistor **160**. The magnitude of $V_2(2\Delta T)$ is measured by observing whether it has dropped sufficiently to turn off a discriminating transistor **160** or not (i.e. whether $V_2(\Delta T)$ is smaller or remains greater than V_{TH} , the threshold of the discriminating transistor **160**.) This will cause the OUTPUT node **91** at a drain of the discriminating transistor **160** to remain at logic HIGH or be pulled to CLK (=0V, logic LOW) respectively.

The state of the OUTPUT node **91** is the sensed result and is stored in a latch **180** when an interconnecting transistor **170** is enabled by a signal STB. See FIGS. 4(L)(5)-4(N)(5).

In the present embodiment the page of memory cells is biased to give a page of memory cells with minimized cell conduction currents so that $I_{MEM}\sim 0$ and $I_{BL}\sim I_{NOISE}$. In

another embodiment, the page of memory cells can be biased to give a page of memory cells with a finite I_{MEM} . For example, in the first sensing phase, $I_{BL}=I_{MEM}+I_{NOISE}$, and in the second sensing phase, $I_{BL}=0.3I_{MEM}+I_{NOISE}$. After the difference is subtracted, it will yield an adjusted $0.7I_{MEM}$ without any I_{NOISE} component.

FIG. 5 is a flow diagram illustrating a method of sensing the conduction current of the memory cell.

STEP 200: Providing a bit line for accessing the memory cell, the bit line having a first bit line current constituted from the conduction current of the memory cell and a current due to noise.

STEP 210: Precharging a capacitor to a first predetermined voltage above a reference voltage.

STEP 220: In a first sensing phase, discharging the capacitor with the first bit line current for a predetermined period of time wherein the first predetermined voltage decreases to a second voltage.

STEP 230: In a second sensing phase, minimizing the conduction current of the memory cell so that the bit line has a second bit line current significantly constituted from the current due to noise, and charging the capacitor with the second bit line current for a same time as the predetermined period of time, wherein the second voltage increases to a third voltage.

STEP 240: Comparing the third voltage with the reference voltage to give a measure of the conduction current of the memory cell.

STEP 250: End.

CLK Signal is to Increase Dynamic Range of the Sensing

In the sense amplifier shown in FIG. 3, the desired bit line voltage is maintained at a constant voltage at V_{BL} by the voltage clamp **70**. For this voltage clamp to function properly, its drain side must be above V_{BL} . This means that the INPUT node **81** will have an operating range from V_x to slightly about V_{BL} . During the first sensing phase, the INPUT node **81** is being discharged by the capacitor C_{SA} **100**. In a preferred embodiment, to prevent the voltage at the INPUT node **81** from ever dropping close to V_{BL} , the voltage at the second terminal of the capacitor C_{SA} **100** is shifted up during the discharge operation.

The sense amplifier **80** shown in FIG. 3 has the clock signal CLK providing a ground voltage reference level for the first terminal of the capacitor C_{SA} **100**. FIG. 4(K) shows the CLK signal to be at 0V at all time in the previous embodiment.

FIG. 6 is a timing diagram illustrating a preferred embodiment for low-voltage operating the sense amplifier **80** shown in FIG. 3. As illustrated in FIG. 6(K')(2), the clock signal CLK is boosted by a predetermined voltage level ΔV during the first phase of sensing. This means during the first phase of sensing as the bit line current is discharging the capacitor C_{SA} **100**, the voltages on both terminals of the capacitor **100** are boosted by ΔV . Thus the voltage on the second terminal is boosted from $V(0)$ to $V(0)+\Delta V$, allowing the discharge operation to be conducted with increase headroom. At the end of the discharge period, the voltage on the second terminal has dropped to $V(\Delta T)+\Delta T$ (see FIG. 6(I')(2)). After the discharge has completed, i.e. after the signal SW2 goes LOW to cut off the bit line current to the second terminal of the capacitor C_{SA} **100** (see FIG. 4(F)(2)), the boosting is then terminated with the signal CLK returning to 0V (FIG. 6(K')(3)). As in shown in FIG. 4(E)(3)-4(E)(4), at this point, the precharge driver **120** is enabled by the signal PC2. This will reset V_2 to $V(0)$ and V_1 shifted by the difference. See FIG. 6(I')(3)-6(K')(3). In the second sensing phase as shown in FIG. 6(J')(4), V_1 is being pulled down by the bit line current I_{BL} . At the end of the second sensing period, V_1 is reset to 0V by connecting back

11

to CLK at node **71**. This will also shift V2 down to the final V2(2ΔT). This final voltage corresponds to the discharging effect of only I_{MEM} on the capacitor C_{SA} **100** and is a measure of I_{MEM} without the interference of I_{NONE}. See FIGS. 4(F)(3) (4)-4(K)(3)(4).

This will restore the voltage on the second terminal to V2(2ΔT). At this time, even if V2(2ΔT) is below V_{BL}, it is isolated from the INPUT node **81** by the disabled transistor **130**. In this way, the voltage at the node **81** is operating with an additional headroom of ΔV while being discharged during the first sensing phase.

FIG. 7 is a flow diagram illustrating another embodiment of the method of sensing the conduction current of the memory cell under low-voltage condition. The method is similar to that illustrated in FIG. 5, except STEP **220** for the first sensing phase is being replaced by the following STEP **220'**.

STEP **220'**: In a first sensing phase, discharging the capacitor with the first bit line current for a predetermined period of time wherein the first predetermined voltage decreases to a second voltage; and wherein the capacitor is provided with first and second terminals, the second terminal being operated at a higher voltage level than the first terminal and with a predetermined boosting voltage applied temporarily to the first terminal during the first sensing phase.

Conclusion

Although the various aspects of the present invention have been described with respect to exemplary embodiments thereof, it will be understood that the present invention is entitled to protection within the full scope of the appended claims.

It is claimed:

1. A method of sensing a conduction current of a memory cell of a non-volatile memory comprising:
 - providing a bit line for accessing the memory cell, the bit line having a first bit line current constituted from the conduction current of the memory cell and a current due to noise;
 - precharging a capacitor to a first predetermined voltage above a reference voltage;
 - in a first sensing phase, discharging the capacitor with the first bit line current for a predetermined period of time wherein the first predetermined voltage decreases to a second voltage;
 - in a second sensing phase, minimizing the conduction current of the memory cell so that the bit line has a second bit line current significantly constituted from the current due to noise, and charging the capacitor with the second bit line current for a same time as the predetermined period of time, wherein the second voltage increases to a third voltage; and
 - comparing the third voltage with the reference voltage to give a measure of the conduction current of the memory cell.
2. The method as in claim 1, further comprising:
 - maintaining the bit line at a predetermined bit line voltage; accessing the memory cell is also by a word line; and wherein said turning off the conduction current includes setting the word line to have a same voltage as the predetermined bit line voltage.
3. The method as in claim 1, wherein:
 - the capacitor is provided with first and second terminals, the second terminal being operated at a higher voltage level than the first terminal; and
 - said discharging the capacitor includes coupling the bit line to the second terminal.

12

4. The method as in claim 1, wherein:
 - the capacitor is provided with first and second terminals, the second terminal being operated at a higher voltage level than the first terminal; and
 - said charging the capacitor includes coupling the bit line to the first terminal.
5. The method as in claim 1, wherein:
 - the capacitor is provided with first and second terminals, the second terminal being operated at a higher voltage level than the first terminal; and
 - said method further comprises: temporarily applying a predetermined boosting voltage to the first terminal during the first sensing phase.
6. The method as in claim 1, further comprising:
 - providing a transistor having a gate and a given threshold to act as the reference voltage; and
 - said comparing the third voltage with the reference voltage is to apply the third voltage to the gate and determine if the transistor is conducting or not.
7. The method as in claim 1, wherein:
 - the memory cell is one of a group of memory cells being sensed in parallel.
8. The method as in claim 1, wherein:
 - the memory cell has a resistance that reversibly shift in resistance in response to a programming voltage applied thereto.
9. The method as in claim 1, wherein:
 - the non-volatile memory is of the NAND type.
10. A sensing circuit for sensing a conduction current of a memory cell of a non-volatile memory comprising:
 - a bit line for accessing the memory cell, the bit line having a first bit line current constituted from the conduction current of the memory cell and a current due to noise;
 - a bit line voltage circuit for maintain the bit line at a predetermined voltage;
 - a capacitor;
 - a precharging circuit coupled to said capacitor to precharge the capacitor to a first predetermined voltage above a reference voltage;
 - in a first sensing phase, a first set of signals enables said capacitor to be coupled for discharging by the first bit line current for a predetermined period of time wherein the first predetermined voltage decreases to a second voltage;
 - in a second sensing phase, where the memory cell has the conduction current minimized so that the bit line has a second bit line current significantly constituted from the current due to noise, and a second set of signals enables said capacitor to be coupled for charging by the second bit line current for a same time as the predetermined period of time, wherein the second voltage increases to a third voltage; and
 - a comparator for comparing the third voltage with the reference voltage to give a measure of the conduction current of the memory cell.
11. The sensing circuit as in claim 10, further comprising:
 - a word line for accessing the memory cell; and
 - wherein the memory cell having the conduction current turned off with the word line having a same voltage as the predetermined bit line voltage.
12. The sensing circuit as in claim 10, wherein:
 - the capacitor has first and second terminals, the second terminal being operated at a higher voltage level than the first terminal; and
 - said first set of signals enables said capacitor to be coupled to the second terminal for discharging by the first bit line current.

- 13.** The sensing circuit as in claim **10**, wherein:
the capacitor has first and second terminals, the second
terminal being operated at a higher voltage level than the
first terminal; and
said second set of signals enables said capacitor to be 5
coupled to the first terminal for charging by the second
bit line current.
- 14.** The sensing circuit as in claim **10**, wherein:
the capacitor has first and second terminals, the second
terminal being operated at a higher voltage level than the 10
first terminal; and
said sensing circuit further comprises:
a clock generator coupled to the first terminal to apply
temporarily a predetermined boosting voltage during
said first sensing phase. 15
- 15.** The sensing circuit as in claim **10**, wherein:
said comparator is a transistor having a gate and a given
threshold to act as the reference voltage, such that the
transistor is conducting when the third voltage is larger
than with the reference voltage and not conducting when 20
the third voltage is less than the reference voltage.
- 16.** The sensing circuit as in claim **10**, wherein:
the memory cell is one of a group of memory cells being
sensed in parallel.
- 17.** The sensing circuit as in claim **10**, wherein: 25
the memory cell has a resistance that reversibly shift in
resistance in response to a programming voltage applied
thereto.
- 18.** The sensing circuit as in claim **10**, wherein:
the non-volatile memory is of the NAND type. 30

* * * * *